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Final Report (01-ERD-051) Dynamic InSAR: Imaging Seismic Waves Remotely from Space

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I. Introduction

This final report summarizes the accomplishments of the originally-planned 2-year project that was cut short to 1 year plus 2 months due to a funding priority change that occurred in the aftermath of the September 11th tragedy. The LDRD-ER project "Dynamic InSAR: Imaging Seismic Waves from Space" (01-ERD-051) began in October, (FY01) and ended in December (FY02). Consequently, most of the results and conclusions for this project are represented in the FY01 Annual Report. Nonetheless, additional conclusions and insights regarding the progress of this work are included in this report. In should be noted that this work was restarted and received additional funding under the NA-22 DOE Nonproliferation Program in FY03.

II. Purpose and Relevance of Project

The purpose of this LDRD project was to determine the feasibility of using InSAR (interferometric synthetic aperture radar) to image seismic waves remotely from space. If shown to be feasible, the long-term goal of this project would be to influence future SAR satellite missions and airborne SAR platforms to include a this new capability.

Most of what we currently understand about the earth—its internal structure and dynamic interior, as well as our understanding of earthquakes and our ability to predict volcanic eruptions, has come from seismology. Seismology also plays a dominant role in monitoring global man-made seismic activity, such as underground mining and nuclear test activity. Seismology, however, is an inherently "blind" methodology, whereby the seismic waves recorded at seismometers are never actually "seen" directly, but are recorded by the effect they have on seismic instruments as the seismic waves pass by. In addition, the relatively sparse spatial sampling on the earth's land surface and nearly complete lack of spatial sampling over the oceans, further limits the information available. If, however, seismic waves could be imaged remotely from space and/or from an aircraft, a spatially continuous "picture" of seismic waves would be available that could greatly increase our understanding of seismic wave propagation, dispersion, and boundary interaction (reflection and refraction). Applications of such a capability relevant to NAI missions include bomb damage assessment/earth-penetrator coupling, underground facility detection, and regional calibration of seismic location correction surfaces for underground nuclear explosion monitoring. Other applications could include earthquake rupture physics, volcano harmonic tremor source characterization, and an open ocean tsunami tracking and early warning system.

III. InSAR Method

Interferometric synthetic aperture radar (InSAR) has become the standard geodetic tool for mapping surface displacements from a variety of sources such as faults, glaciers, fluid reservoirs (oil, gas, geothermal, volcanic) as well as from soil compaction from aquifer discharge and recharge. The quasi-continuous maps of surface displacement provide the added constraints needed to produce more accurate models of these sources.

Figure 1 shows the basic scanning geometry of a space-borne SAR where a radar backscatter map is formed by scanning the Earth's surface in a side-looking fashion. As the satellite sensor moves along its orbital path with velocity **Vs**, it transmits microwave pulses and echoes are received from each pulse at the same antenna. The region on the ground illuminated by a single pulse is referred to as the antenna footprint and the entire imaged strip is called the swath. SAR data are divided into 100 km by 100 km frames and are processed one-at-a-time. Once processed, individual frames can be combined interferometrically with those from another (repeat) orbit and the resulting phase difference will be proportional to the change in range to the satellite from each ground pixel (25m x 25m) that occurred between imaging times (after topographic phase is removed). From this information, a geo-referenced surface deformation map can be produced with sub-centimeter sensitivity and 30 meter resolution. It is these deformation maps, or interferograms, that allow for the construction of more accurate source models by constraining the surface deformation these models are allowed to predict.

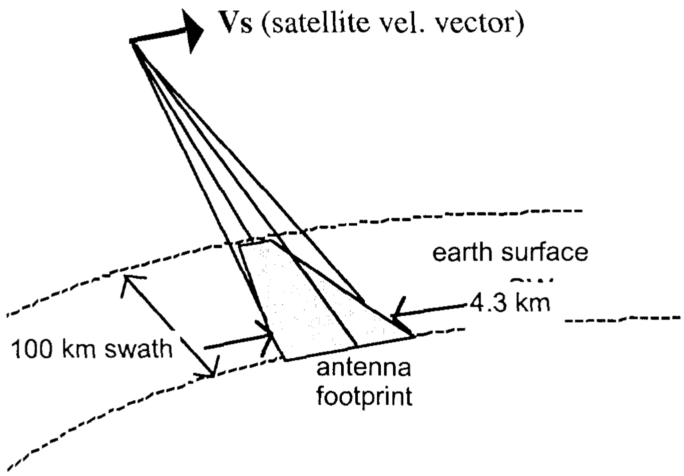

Figure 1. Imaging geometry of a space-borne SAR (swath width and antenna footprint are given for the commercial ERS-1 SAR satellite; Not-to-scale).

IV. Dynamic InSAR Method

While *static* InSAR measures the total accumulated surface displacement field between repeat-pass orbit imaging times, *dynamic* InSAR measures the dynamic displacements that occur in real time during one of the two individual SAR image collections. Alternatively, two antennas can be mounted on a single SAR platform so that only one pass is needed to capture topography changes dynamically (e.g., water waves). For example, a dynamic InSAR system has measured the motion (velocity) of water waves on the ocean surface just off shore from Point Loma, CA using two SAR antennas, spaced 20 meters apart along the underside of the fuselage of NASA's DC-9 AirSAR aircraft [Goldstein, et al, in *Nature*, 1989]. Seismic waves, however, move much faster, and with much smaller vertical displacements that water waves. This renders the configuration used by JPL scientists to image water waves (i.e., with two SAR antennas separated by 20 meters) useless because the interferometric phase would change much too rapidly to maintain coherence and avoid phase cycle ambiguities. Given this limitation, our approach was to try to capture an earthquake-generated Rayleigh wave in a single satellite pass.

The first step toward achieving this goal was to use commercially available archived SAR satellite data to try to produce an InSAR image of a seismic wave from a past seismic source such as an earthquake or explosion. In principle, this could be done by interfering a SAR data collection that captures a seismic wave in one orbit pass with another SAR image of the same ground region from another orbit—the phase difference between these two SAR images should result in only the seismic wave perturbation being present. The challenge was to find an archived SAR image that captured a 3-8 km/sec moving seismic wave in its image frame. To do this the precise space-time location of a candidate seismic wave is accurately predicted as a function of distance from its source, and an intersection was is found with the satellite imaging swath where the intersection must occur before the seismic waves decays below InSAR detection thresholds. We developed the algorithms to do this search and our intersection accuracy out 180 degrees from the source was better than 10 seconds (as verified by seismic station recordings closest to our intersection points). We found SAR data for two such candidate intersections, but the predicted displacements were only one millimeter, and while on land, the area contained either vegetation or snow and consequently the data was deemed not worth purchasing.

In the second half of the (shortened) project period, we began working on a controlled, triggered seismic wave SAR collection experiment. To determine the expected surface displacements from an explosive source, we collected seismic data from large 40k lbs rocket motor detonations conducted at the Utah Test and Training Range near Salt Lake (see Figure in LDRDFY00 Annual Report). Theses data, along with our simulations using LLNL's E3D seismic simulation code, was used to calibrate a future SAR collection experiment. At this point the project ended prematurely as explained above. While we did not have enough time to fulfill our object, we did make significant progress and have continued this work under alternative funding.

V. Future Work

This work is continuing under different funding as described above.